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IMPLICATIONS OF A PRIMORDIAL ORIGIN FOR THE DISPERSION IN D/H IN QUASAR ABSORPTION SYSTEMS

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ABSTRACT

We consider possible implications if the recent and disconcordant measurements of D/H in quasar absorption systems are real and indicate a dispersion in D/H in these primitive systems. In particular we examine the option that the D/H abundances in these systems, which are separated on cosmological scales, are primordial, implying a large scale inhomogeneity in the baryon content of the Universe. We show that such large scale isocurvature perturbations are excluded by current cosmic microwave background observations. We also discuss the implications of a smaller (in amplitude) inhomogeneity on the problem of the baryon density in clusters.

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There has been a recent flurry of activity in measurements of potentially primordial D/H in quasar absorption systems. If the measured values of D/H are in fact primordial, then they are of paramount importance to big bang nucleosynthesis (BBN) since the predicted D/H abundance is a rapidly varying and monotonic function of the single unknown parameter in the standard model, namely the baryon-to-photon ratio, η (see eg. Walker *et al.* 1991 and reference therein). An independent determination of η, in addition to enabling a critical test of BBN based on the other light element isotopes (Reeves *et al.* 1973), has far reaching consequences on the nature of dark matter and the composition of galactic halos. A simple interpretation based on the recent D/H measurements, however, is complicated by the fact that they are not uniform. In fact, they span an order of magnitude in D/H and, as such taken separately, lend themselves to very different cosmological interpretations. Nevertheless, all measurements are consistent with the basic BBN prediction that deuterium is primordial and the nucleosynthetic prediction (Reeves *et al.* 1973; Epstein, Lattimer, & Schramm 1976) that the primordial D/H ratio is higher than present day values. However, the different extra-galactic measurements, if proven universal, would imply very different chemical evolution histories with high primordial values indicating large amounts of stellar processing and lower values indicating perhaps that our Galaxy is presently receiving primordial infall. While it is necessary to be highly cautious at this stage (as is the case with any new set of data), and indeed any one (or all) of the reported measurements may not represent the primordial abundance of D/H, here we entertain the alternate (and even more exotic as we shall see) possibility that both the high and low D/H measurements are accurate and uncontaminated. Indeed, it has been suggested (Cardall & Fuller 1996; Fuller & Cardall 1996; Tytler & Burles 1996) that a possible explanation of differing measurements of primordial D/H, is the presence of an inhomogeneity in the baryon number on very large (cosmological) scales. We will explore the implications of an inhomogeneity on the cosmic microwave background, where, if allowed, we would then expect a dispersion in the height of the Doppler peak to be observable.

In the past two years there have been several measurements of D/H in high redshift quasar absorption systems. In the first of these measurements (Carswell *et al.* 1994; Songaila *et al.* 1994) a surprisingly high value of $\log \mathrm{D/H} \simeq -3.92\,\mathrm{to} - 3.32$ was reported along the line of sight of Q0014+813 at $z = 3.32$. The value of η corresponding to this abundance is low, $\eta_{10} = 10^{10}\eta \simeq 1.7$ and was unexpected on the basis of older arguments revolving around the evolution of D and ^{3}He (Walker *et al.* 1991). Observations of a ^{3}He/H ratio in planetary nebulae (Rood, Bania & Wilson 1992; Rood *et al.* 1995) indicate the need for at least some substantial stellar production of ^{3}He and and thereby necessarily complicate the evolution of ^{3}He (see eg. Olive *et al.* 1995; Scully *et al.* 1996). However, ^{3}He measurements in meteorites

(Geiss 1993), Galactic HII regions (Balser *et al.* 1994) and the recent ISM measurement of Gloeckler & Geiss (1996), have cast doubt on traditional ^{3}He production in low mass stars (evidenced in the observations of planetary nebulae) and thus the possibility of high D/H no longer causes conflict on theoretical grounds since the evolution of ^{3}He is now suspect. Furthermore, an early report of a significantly lower D/H abundance in a different quasar absorption system (Tytler & Fan 1995) and the possibility that the high D/H observation was caused an interloping cloud (Steigman 1994) cast reserve on the measurements.

A recent reanalysis (Rugers & Hogan 1996a) of the absorber at $z = 3.32$ revealed in fact two distinct components each with the same high D/H abundance giving $\log \mathrm{D/H} = -3.72 \pm 0.10$ for the average of the two. The possibility of a hydrogen interloper is thus much less likely. Subsequently, there have been several other reported measurements of D/H in other quasar absorption systems. In a system at $z = 3.08$ in the direction of Q0420-388, Carswell *et al.* (1996) observe D/H in two close components which both show a high abundance for D/H (1.0 and 2.5 $\times 10^{-4}$) and when they assume a common ratio for O/H in the two components (at about 1/10th solar) obtain $\log \mathrm{D/H} = -3.7 \pm 0.1$ consistent with the previous high determination. They note however, that uncertainties in the H column density could allow values as low as -4.70. In yet another system at very high redshift, $z = 4.69$, along the line of sight of BR1202-0725 Wampler *et al.* (1996) report a D/H abundance consistent with the other high determinations but quote only an upper bound of -3.82. Also, Songaila & Cowie find $\mathrm{D/H} \approx 2 \times 10^{-4}$ in an absorber in Q0956+122, Rugers & Hogan (1996b) report $\log \mathrm{D/H} = -3.95 \pm 0.54$ in a $z = 2.89$ absorber in GC0636+680. Finally, with respect to high D/H determinations, Rugers & Hogan (1996c) have reported a new observation of D/H in a $z = 2.80$ absorber again along the line of sight of Q0014+813 with $\log \mathrm{D/H} = -3.73 \pm 0.28$.

There are also quasar absorption systems for which D/H is measured to be considerably smaller than the high values around 2×10^{-4}. In the direction of Q1937-1009, Tytler, Fan & Burles (1996) report a value of $\log \mathrm{D/H} = -4.64 \pm 0.06^{+0.05}_{-0.06}$ in a $z = 3.57$ absorber. Burles & Tytler (1996) find $\log \mathrm{D/H} = -4.60 \pm 0.08 \pm 0.06$ in a $z = 2.50$ absorber in Q1009+2956. As one can see, there is a clear discrepancy between the high and low D/H determinations. The available data on D/H in quasar absorption systems is summarized in figure 1.

Implications of either the high D/H measurements or the low D/H measurements have been discussed relative to BBN and dark matter (Vangioni-Flam & Cassé 1995; Hata *et al.* 1996; Cardall & Fuller 1996; Fuller & Cardall 1996; Schramm & Turner 1996). In a recent analysis of BBN for $N_\nu = 3$ based on ^{4}He and ^{7}Li, the two isotopes which rely least on evolution, Fields & Olive (1996) and Fields *et al.* (1996), determined the range in η which best fits these abundances of these two isotopes as taken directly from the data. They found

$\eta_{10} = 1.8^{+2.0}_{-0.4}$ (for a 95% CL range). This corresponds to the range D/H = (0.55–2.8) $\times 10^{-4}$ with a best value sharply peaked at 1.8×10^{-4} and is in excellent agreement with the higher observed D/H seen in *some* of the QSO absorbers. However, such a low value of η becomes more problematic for the evolution of ^{3}He which appears to be relatively flat over the last 5 Gyr history of the galaxy (Turner *et al.* 1996). We emphasize that when the production of ^{3}He in low mass stars is included in chemical evolution models (Olive *et al.* 1995; Galli *et al.* 1995; Scully *et al.* 1996; Dearborn, Steigman & Tosi 1996) even higher values of η (lower values of primordial D/H) are problematic and the issue of the evolution of ^{3}He becomes a question for stellar evolution (Charbonel 1994, 1995; Hogan 1995; Wasserburg, Boothroyd, & Sackman 1995; Weiss *et al.* 1995; Boothroyd & Sackman 1995; Boothroyd & Malaney 1995).

The low D/H determinations also can be problematic for BBN using a straight interpretation of the data. Although the low D/H does relax to some extent the problem of ^{3}He evolution (Scully *et al.* 1996), there may be problems with the abundances of the other light elements. Because the observationally determined values with their published systematic errors of ^{4}He and ^{7}Li fit very well with the high D/H measurements, the combined likelihood of all three isotopes when convolved with the BBN calculations is extremely high (Fields *et al.* 1996). To get a comparable likelihood, the ^{4}He determinations would have to be systematically low by 0.015, that is as opposed to the value $Y_p = 0.234 \pm 0.003$ for the ^{4}He mass fraction (Olive & Steigman 1994; Olive & Scully 1996), the central value for Y_p would need to be raised to 0.249, a value which is high even when a generous assessment of the systematic errors is made (Copi, Schramm, & Turner 1995). Furthermore, ^{7}Li/H would need to be as high as 5 $\times 10^{-10}$ requiring as much as a factor of 3 depletion which may be problematic (Steigman *et al.* 1993).

There is of course the possibility that either (or both) the high or low D/H determinations are not an accurate indication of primordial D/H as it pertains to BBN. Potential problems with the high D/H observations have been outlined by Burles & Tytler (1996) and include uncertainties in the hydrogen column density which can lead to a serious over estimate of the D/H ratio. This is a chief uncertainty in the case of Q0420-388 and one of the reasons that this observation is consistent with the low D/H measurements. The absorber in BR1202-0725 has relatively high metallicity ([O/H] = 0.3) which casts doubt on its primordial nature (though this would indicate a potentially higher D/H) and the lack of metal lines in the spectra of Q0014+813 casts some uncertainty on the accuracy of these abundances.

The low D/H measurements are also subject to considerable uncertainty. As pointed out by Rugers & Hogan (1996c), the gas mass covering the quasar image is very small (less than a solar mass). Thus the ejecta of a single intermediate mass star (3–8 $M_\odot$) which is both

deuterium free and heavy element free can greatly affect the measurement of D/H. Clearly such an effect would lower the D/H ratio in an absorber. In addition, the abundances in the two recent low D/H systems of Tytler, Burles & Fan (1996) and Burles & Tytler (1996) are based on blended lines where it was assumed that the D/H was uniform in the two components. Other assumptions could increase the implied D/H ratio. It fact, it has been recently argued (Wampler 1996), that alternative cloud models could raise the low D/H abundances by a factor of 3–6. A factor of 6 would make them compatible (within errors) of the high D/H measurements. It is clear that the most prudent course of action is to treat with some reserve all of the QSO absorption system measurements of D/H. Hopefully, with increased statistics, a better understanding of the measurements and the D/H will be available. One would further expect that either the observers finding high D/H should begin to see some systems with low D/H, vice versa, or both.

Given the appropriate amount of caution regarding these measurements, let us now assume that *all* of the D/H measurements in quasar absorption systems are in fact, accurate. Therefore we may ask, can the value of primordial D/H differ in these systems. In the remainder of this letter, we would like to detail the consequences of this assumption.

As we stated earlier, the BBN prediction for primordial D/H is a very rapidly changing monotonic function of the baryon-to-photon ratio, η. As such, any measurement with some degree of confidence of primordial D/H, can in principle very accurately pin down the value of η. If there is a real dispersion in primordial D/H as would be the case if both the high and low D/H measurements were accurate, then we have evidence for the first time of a real inhomogeneity in the baryon number on large scales. In addition, the amplitude of the fluctuations producing these inhomogeneities must be large ($\mathcal{O}(1)$) at the time of BBN as the D/H dispersion corresponds to values of η from ~ 1.5 to ~ 7.0. The various QSO absorption systems in which the D/H measurements are made are all at large redshift (ranging from $z = 2.5$–4.7) and are thus separated by cosmological distance scales. We stress that inhomogeneities on scales as large as this are very different from the adiabatic baryon inhomogeneities inspired from the QCD phase transition (see eg. Malaney & Mathews 1993; Thomas *et al.* 1994) and from the small scale baryon isocurvature fluctuations (Kurki-Suonio, Jedamzik, & Mathews 1996) that give rise to inhomogeneous BBN. In these cases the inhomogeneities were produced on small scales (sub-horizon at the time of BBN), while the inhomogeneities we are considering must be nearly horizon scale today, meaning that these are inhomogeneities on scales much larger than the horizon at the time of BBN. That is, within a horizon at the time of BBN, we are still dealing with homogeneous BBN. Nucleosynthesis with large scale inhomogeneities has been considered recently (Copi, Olive, & Schramm 1995; Jedamzik & Fuller 1995). These studies focused on inhomogeneities that

have mixed and would not lead to inhomogeneities in the observed abundances.

We would also like to emphasize the implications of a large scale baryon inhomogeneity of the type we have been discussing on standard BBN. The abundance of a single light element isotope which can be associated with its primordial value is enough to constrain BBN and determine a value for η. To test the theory, we need the abundances of two or more light element isotopes. For example, this can be and is achieved using ^{4}He and ^{7}Li (Fields & Olive 1996). If the Universe were homogeneous in baryon number, then a primordial measurement of D/H in quasar absorption systems would lead to strong test of the theory. However, if the dispersion in D/H in these systems is real and indicates a real large scale baryon inhomogeneity, then unless a second isotope (eg. ^{4}He or ^{7}Li) can be observed in the *same* absorption system, the D/H measurements will yield information regarding the baryon-to-photon ratio in those systems, in addition to information on the inhomogeneity. These measurements alone could not be used to test BBN as they could not be directly compared to the predictions based on ^{7}Li, which is observed in our own Galaxy, or ^{4}He, which though is observed in external galaxies, these are all relatively local (ie. they are all at very low redshift).

One important and viable mechanism for the production of the baryon asymmetry of the Universe is realized in supersymmetric extensions of the standard model of electroweak interactions (Affleck & Dine 1985; Linde 1985a; Ellis *et al.* 1987). The minimal supersymmetric standard model contains many additional particle degrees of freedom over the standard model, corresponding to the supersymmetric partners of ordinary particles. The potential for the scalar fields contains directions for which the potential is perfectly flat, that is, certain combinations of these fields are allowed to take arbitrarily large vacuum expectation values at little (or none, if supersymmetry is unbroken) cost in energy. During inflation, De Sitter fluctuations drive these scalar fields to large expectation values and the subsequent evolution of these fields (which store baryon and lepton number) produces a baryon asymmetry. The final baryon asymmetry is in general quite model dependent as it depends on quantities such as the expectation value produced by inflation, the inflaton mass, the grand unified mass scale, and the supersymmetry breaking mass scale.

In the course of the evolution of the scalar fields, sfermion density fluctuations are produced (Ellis *et al.* 1987; Yokoyama 1994) which lead to isocurvature fluctuations in the baryon density with an amplitude which is given by (Linde 1985b)

$$\frac{\delta n_B}{n_B} = \frac{\delta \rho_\phi}{\rho_\phi} \simeq \frac{\delta\phi(k)}{\phi} \simeq (H/\phi_o)(k/H)^{\tilde{m}^2/3H^2} \tag{1}$$

where H is the Hubble parameter during inflation, $\tilde{m}$ is the sfermion mass, and ϕ_o is the

vacuum expectation value of the sfermion fields, ϕ, produced during inflation. Thus, isocurvature baryon number fluctuations are produced with an amplitude which depends primarily on the ratio H/ϕ_o and may take values from $\sim 10^{-8}$ to ~ 1. In order to have an impact on the D/H abundances, $\delta n_B/n_B$ must take values of order 1, however, smaller values though not important for D/H, may still have significant cosmological consequences for the density of baryons in clusters of galaxies. We will return to this point below, but for now we will assume $\delta n_B/n_B \sim 1$.

The overall baryon to entropy ratio is given by (Ellis *et al.* 1987)

$$\frac{n_B}{s} = \frac{\phi_o^4 m_\psi^{3/2}}{M_G^2 M_P^{5/2} \tilde{m}} \sim 10^{-11} \tag{2}$$

for $\phi_o \sim 10^{-6} M_P$, an inflaton mass, $m_\psi \sim \phi_o$, a GUT mass of order $10^{-3} M_P$, and a sfermion mass, $\tilde{m}$, of order 100 GeV. First it is important to stress that in models such as these,the baryon density $\rho_B \ll \rho_{\rm total}$ so that even though $\delta\rho_B/\rho_B$ may be of order unity (if $H \sim \phi_o$), $\delta\rho_B/\rho_{\rm total} \sim 10^{-9}$ is very small at the time the sfermion oscillations have decayed, and $\rho_{\rm total}$ is the total energy density which is dominated by the dynamics of inflation. Second, the spectrum of isocurvature perturbations in the baryons is very nearly flat, since $\tilde{m}/H \ll 1$, is present on exponentially large scales, and is completely independent of the adiabatic fluctuations produced by inflation. Note that adiabatic perturbations do not influence BBN since $\delta\eta/\eta = 0$. (More accurately, $\delta(n_B/s) = 0$ for adiabatic perturbations.) Thus, the overall large scale structure believed to have been seeded by inflation remains a flat adiabatic spectrum of density fluctuations. Baryons, however have in addition an isocurvature component with an amplitude which may be of order unity. Such a model provides a plausible physical origin for baryon inhomogeneities on very large scales.

To explain the dispersion in D/H as seen in different quasar absorption systems we require large scale inhomogeneities at the time of nucleosynthesis. Since these quasar absorption systems are observed along different lines of sight the isocurvature power spectrum must have significant power on angular scales $\theta \gtrsim \mathcal{O}(\text{few})$ degrees. Furthermore they must be created with a large amplitude since they must be in place at the onset of BBN to generate the observed dispersion in D/H. Thus the scales we are considering enter the horizon after last scattering and they will induce fluctuations in the CMB due to the inhomogeneities in the gravitational potential from the variations in the baryon density, i.e. the Sachs-Wolfe effect, on scales $\theta \gtrsim \theta_{\rm LS} \sim 2°$.

The total temperature fluctuations in the CMB for isocurvature perturbations including the intrinsic fluctuations and those induced by the Sachs-Wolfe effect are

$$\frac{\delta T}{T} \approx 2\delta\phi, \tag{3}$$

where $\delta\phi$ is the Newtonian potential (Hu & Sugiyama 1995). This expression is accurate to $\sim 10\%$. For isocurvature perturbations the fluctuations in the potential are

$$\delta\phi \sim \frac{G\delta M}{\lambda} \sim \frac{1}{2}H^2\Omega_B\lambda^2\frac{\delta n_B}{n_B} \sim \frac{2}{3}\Omega_B\left(\frac{\rho_R}{\rho_B}\right)\delta \tag{4}$$

at the time when a scale $\lambda \sim H^{-1}$ enters the horizon. Here

$$\delta \equiv \frac{\delta\left(n_B/s\right)}{n_B/s} \sim \frac{3}{4}\frac{\rho_B}{\rho_R}\frac{\delta n_B}{n_B} \sim \frac{\delta\eta}{\eta} \tag{5}$$

is the fluctuation in the number of baryons per comoving volume and ρ_R is the energy density in radiation at late times. This expression (5) is valid for $\rho_B \gg \rho_R$. The temperature fluctuations are suppressed by two effects. First by the density of baryons in the Universe, Ω_B, which create the potential well. The second suppression comes from the fact that super-horizon sized perturbations cannot grow since $\delta\rho = 0$.

As one can see from Eq.(4), the potential fluctuations $\delta\phi$ are time independent on a particular scale λ, prior to horizon crossing as $\lambda^2\delta n_B/n_B \propto R^3 \propto t^2$, and $H^2 \propto t^{-2}$. However as can also be seen from (4), these fluctuations are scale dependent. Prior to horizon crossing, the suppression factor (ρ_R/ρ_B) induces a scale dependence and we can scale $\delta\phi$ to the present by noting that $\delta\phi \propto R^{-1}$ and that the scale λ enters the horizon at a time $t \propto \lambda^3$. Since $R \propto t^{2/3}$ in the matter dominated era

$$\delta\phi = \left(\frac{\lambda_0}{\lambda}\right)^2\delta\phi_0 \tag{6}$$

in terms of the potential fluctuations today, $\delta\phi_0$. For $\lambda_0 \sim H_0^{-1}$ and $\delta \sim 1$ the restriction $\delta T/T \lesssim 10^{-5}$ leads to $\lambda \gtrsim 2.4\lambda_0$. This is our main result. The large scale, large amplitude baryon inhomogeneity needed to explain the apparent dispersion in the D/H abundances measured in quasar absorption systems makes a contribution to the microwave background anisotropy induced by the Sachs-Wolfe effect which is in excess of the observed anisotropy for all scales $\lambda < \lambda_0 \sim H_0^{-1}$ that have entered the horizon.

On angular scales somewhat smaller than 2°, the Sachs-Wolfe effect is not operative but a similar constraint may be derived. For scales which enter the horizon between the epochs of matter domination and last scattering, ie between $\sim 20' h^{-1}$ and 2°, corresponding to length scales between $\sim 35h^{-2}$ Mpc and 200 h^{-1} Mpc, there is a contribution to $\delta T/T$ which is due to Doppler shifts across fluctuations at last scattering. This gives (Silk 1991)

$$\frac{\delta T}{T} \sim \frac{v}{c} \sim H\Omega_B\lambda\frac{\delta n_B}{n_B} \sim \Omega_B\delta \tag{7}$$

Thus large fluctuation in n_B/s are excluded at these scales as well.

To avoid these CMB constraints we need to consider smaller scales where the fuzziness of the last scattering surface suppresses temperature fluctuations so that at scales below $30''$ the fluctuations are acceptably small. Alternatively we can consider scales that have not yet been probed by the CMB. However we do not want to consider scales that are so small that many such perturbations would make up one quasar absorption cloud. In this case we would expect the regions to mix. Observations in our Galactic neighborhood preclude this mechanism from producing the large fluctuations in the D/H abundance (Copi, Olive, & Schramm 1995; Jedamzik & Fuller 1995). Very large fluctuations mix in regions with high ^{7}Li abundances producing a final abundance inconsistent with present observations. Fluctuations with $\delta \lesssim 0.15$ can be made consistent with the light element abundances (Copi, Olive, & Schramm 1995) but are not sufficiently large to explain the observed QSO D/H abundance variations.

To circumvent both of these bounds one is forced to consider a scale in the middle; large enough to encompass an entire quasar absorption cloud, but small enough to avoid the CMB bounds. This leaves us only with a scale of ~ 1 Mpc which corresponds to $\theta \sim 30''$ at last scattering. Extra-galactic HII regions, the best sites for observing ^{4}He have been probed on these scales. Both D and ^{7}Li have been probed in our Galactic neighborhood on scales smaller than this. Thus we would not expect to see variations in the observed Galactic D and ^{7}Li abundances but would expect to see them in the observed ^{4}He abundances. Observations from the lowest metallicity extra-galactic HII regions are consistent with a scatter of $\delta Y_p \sim 0.01$ which corresponds to $\delta\eta \sim 3$. However the uncertainties are large and the scatter is consistent with the assigned error bars of individual ^{4}He measurements.

We note that picking out a single scale for the baryon number fluctuations strays far from our original motivation of flat directions from supersymmetry which generally lead to a *flat* spectrum on very large scales. Thus, we cannot motivate the $30''$ scale from the model described above. As we noted above however, such a model may produce fluctuations with significantly smaller amplitudes. Baryon inhomogeneities of this type would affect the ratio of the baryon mass to the total mass as measured by the x-ray emission of hot gas in clusters of galaxies.

In the model for baryon number fluctuations described above, though the amplitude for isocurvature fluctuations is contrained so that it may not explain the possible dispersion in D/H, these fluctuations may be present with a smaller amplitude. As such, these isocurvature baryon number fluctuations are: 1) expected to have a flat spectrum; 2) are Gaussian distributed, ie they are random and; 3) most importantly, they are completely independent of the overall dark matter fluctuations (eg. due to adiabatic fluctuations produced during inflation). Thus, we would generally expect a higher baryon to dark matter ratio in clusters

than the Universal average. Note that adiabatic fluctuations do not lead to these types of variations since $\delta n_B/n_B = \delta n_{\rm CDM}/n_{\rm CDM}$ so the ratio remains constant. In fact, we would expect the ratio $M_{\rm hotgas}/M_{\rm tot}$ to be different in different clusters which is consistent with the wide variations see in current observations (Mushotzky 1996, or see for example Wu & Fang 1996), though one must be cautious since different observations may not be directly comparable (Evrard, Metzler, & Navarro 1995). On the other hand, such variations are hard to understand in traditional cold dark matter models, since cluster scales are supposed to be fair samples of the overall matter distribution and it is assumed that there is a common source for the fluctation spectrum.

At present the observations of deuterium in quasar absorption systems roughly fall around two values that differ by an order of magnitude. Though it is premature to identify either (or any) set of observations as primordial we consider the possibility that both are correct and are primordial. To be primordial we need large scale, large amplitude isocurvature perturbations. Standard BBN would then lead to the observed dispersion in D/H. Supersymmetry provides one model where the required isocurvature spectrum can be produced.

For scales that enter the horizon after last scattering, $\theta > \theta_{\rm LS} \sim 2^\circ$, the dominant contribution to the CMB is the Sachs-Wolfe effect. Perturbations on all scales that have entered the horizon after last scattering that could explain the D/H dispersion lead to CMB fluctuations that are larger than observed. For scales smaller than this, $20' h^{-1} \lesssim \theta \sim 2^\circ$, Doppler shifts across fluctuations at last scattering would also be too large for these fluctuations. Only on smaller scales can the CMB limits be avoided. However scales smaller than those of a quasar absorber would be well mixed thus homogenizing the BBN products. Fluctuations of the amplitude we are considering here are not possible due to light element constraints (Copi, Olive, & Schramm 1995; Jedamzik & Fuller 1995). Only on scales $\lambda \sim$ 1 Mpc, $\theta \sim 30''$ can we avoid all constraints. Observations of ^{4}He in extra-galactic HII regions probe these scales but the data is too uncertain to test for these perturbations. Even so, we do not have a model that will produce large amplitude perturbations on just these scales.

Although large amplitude, large scale perturbations leave excessive imprints on the CMB, smaller amplitude perturbations would not. Smaller amplitude perturbations cannot explain the D/H dispersion but can address the cluster baryon problem. Cluster scale isocurvature perturbations can explain different $M_{\rm hotgas}/M_{\rm tot}$ ratios in clusters that cannot be understood in the standard cold dark matter scenarios.

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References

Affleck, I. & Dine, M. 1985, Nucl. Phys., B249, 361.

Balser, D.S., Bania, T.M., Brockway, C.J., Rood, R.T., & Wilson, T.L. 1994, ApJ, 430, 667.

Boothroyd, A.I. & Malaney, R.A. 1995, astro-ph/9512133.

Boothroyd, A.I. & Sackman, I.-J. 1995, astro-ph/9512121.

Burles, S. & Tytler, D. 1996, astro-ph/9603070.

Cardall, C.Y. & Fuller, G.M. 1996, astro-ph/9603071.

Carswell, R.F., Rauch, M., Weymann, R.J., Cooke, A.J. & Webb, J.K. 1994, MNRAS, 268, L1.

Carswell, R.F., *et al.* . 1996, MNRAS, 278, 518.

Charbonnel, C. 1994, A & A, 282, 811.

Charbonnel, C. 1995, ApJ, 453, L41.

Copi, C.J., Olive, K.A., & Schramm, D.N. 1995, ApJ, 451, 51.

Copi, C.J., Schramm, D.N., & Turner, M.S. 1995, Science, 267, 192.

Dearborn, D., Steigman, G. & Tosi, M. 1996, ApJ, 465, in press.

Ellis, J., Enqvist, K., Nanopoulos, D.V. & Olive, K.A. 1987, Phys. Lett., B191, 343.

Epstein, R., Lattimer, J., & Schramm, D.N. 1976, Nature, 263, 198.

Evrard, A.E., Metzler, C.A., & Navarro, J.F. 1995, astro-ph/9510058.

Fields, B.D. & Olive, K.A. 1996, Phys Lett B368, 103.

Fields, B.D., Kainulainen, K., Olive, K.A., & Thomas, D. 1996 New Astronomy, in press.

Fuller, G.M. & Cardall, C.Y. 1996, astro-ph/96006025.

Galli, D., Palla, F. Ferrini, F., & Penco,U. 1995, ApJ, 433, 536.

Geiss, J. 1993, in *Origin and Evolution of the Elements* eds. N. Prantzos, E. Vangioni-Flam, & M. Cassé (Cambridge: Cambridge University Press), p. 89.

Gloeckler, G. & Geiss, J. 1996, Nature, 381, 210.

Hata, N., Stiegman, G., Bludman, S., & Langacker, P. 1996, astro-ph/9603087.

Hu, W. & Sugiyama, N. 1995 PRD, 51, 2599.

Hogan, C.J. 1995, ApJ, 441, L17.

Jedamzik, K. & Fuller, G.M. 1995, ApJ, 452, 33.

Kurki-Suonio, H., Jedamzik, K., & Mathews, G.J. 1996, astro-ph/9606011.

Linde, A.D. 1985a, Phys. Lett., B160, 243.

Linde, A.D. 1985b, Phys. Lett., B158, 375.

Malaney, R. A. & Mathews, G. 1993, Phys. Rep., 229, 147.

Mushotzky, R.F. 1996, talk given at the Berkeley Conference on the Baryonic Content of the Universe.

Olive, K.A., Rood, R.T., Schramm, D.N., Truran, J.W., & Vangioni-Flam, E. 1995, ApJ, 444, 680.

Olive, K.A., & Scully, S.T. 1996, Int. J. Mod. Phys., A11, 409.

Olive, K.A., & Steigman, G. 1995, ApJS, 97, 49.

Reeves, H., Audouze, J., Fowler, W.A., & Schramm, D.N. 1973, ApJ, 179, 909.

Rood, R.T., Bania, T.M., & Wilson, T.L. 1992, Nature, 355, 618.

Rood, R.T., Bania, T.M., Wilson, T.L., & Balser, D.S. 1995, in *the Light Element Abundances, Proceedings of the ESO/EIPC Workshop*, ed. P. Crane, (Berlin:Springer), p. 201.

Rugers, M. & Hogan, C. 1996a, ApJ, 259, L1.

Rugers, M. & Hogan, C. 1996b, in *Cosmic Abundances*, proceedings of the 6th Annual October Astrophysics Conference in Maryland, PASP conference series, in press.

Rugers, M. & Hogan, C. 1996c, astro-ph/9603084.

Scully, S.T., Cassé, M., Olive, K.A., Schramm, D.N., Truran, J., & Vangioni-Flam, E. 1996, ApJ, 462, 960.

Silk, J. 1991, Phys. Scr., 36, 16.

Schramm, D.N. & Turner, M.S. 1996, Nature, 381,193.

Songaila, A., Cowie, L.L., Hogan, C. & Rugers, M. 1994 Nature, 368, 599.

Steigman, G. 1994, MNRAS, 269, L53.

Steigman, G., Fields, B. D., Olive, K. A., Schramm, D. N., & Walker, T. P., 1993, ApJ 415, L35.

Thomas, D., Schramm, D. N., Olive, K. A., Mathews, G. J., Meyer, B. S. & Fields, B. D. 1994, ApJ, 406, 569.

Turner, M.S., Truran, J.W., Schramm, D.N., & Copi, C.J. 1996, astro-ph/9602050.

Tytler, D. & Burles, S. 1996, astro-ph/9606110.

Tytler, D. & Fan, X.-M. 1995, BAAS, 26, 1424.

Tytler, D., Fan, X.-M., & Burles, S. 1996, astro-ph/9603069.

Vangioni-Flam, E. & Cassé, M. 1995, ApJ, 441, 471.

Walker, T. P., Steigman, G., Schramm, D. N., Olive, K. A., & Kang, H. 1991, ApJ, 376, 51.

Wampler, E.J. *et al.* 1996, astro-ph/9512084, AA, in press.

Wampler, E.J. 1996, scientific correspondence submitted to Nature.

Wasserburg, G.J., Boothroyd, A.I., & Sackmann, I.-J. 1995, ApJ, 447, L37.

Weiss, A., Wagenhuber, J., & Denissenkov, P. 1995, astro-ph/9512120.

Wu, X.-P. & Fang, L.-Z. 1996, astro-ph/9606109.

Yokoyama, J. 1994, AstroParticle Phys, 2, 291.

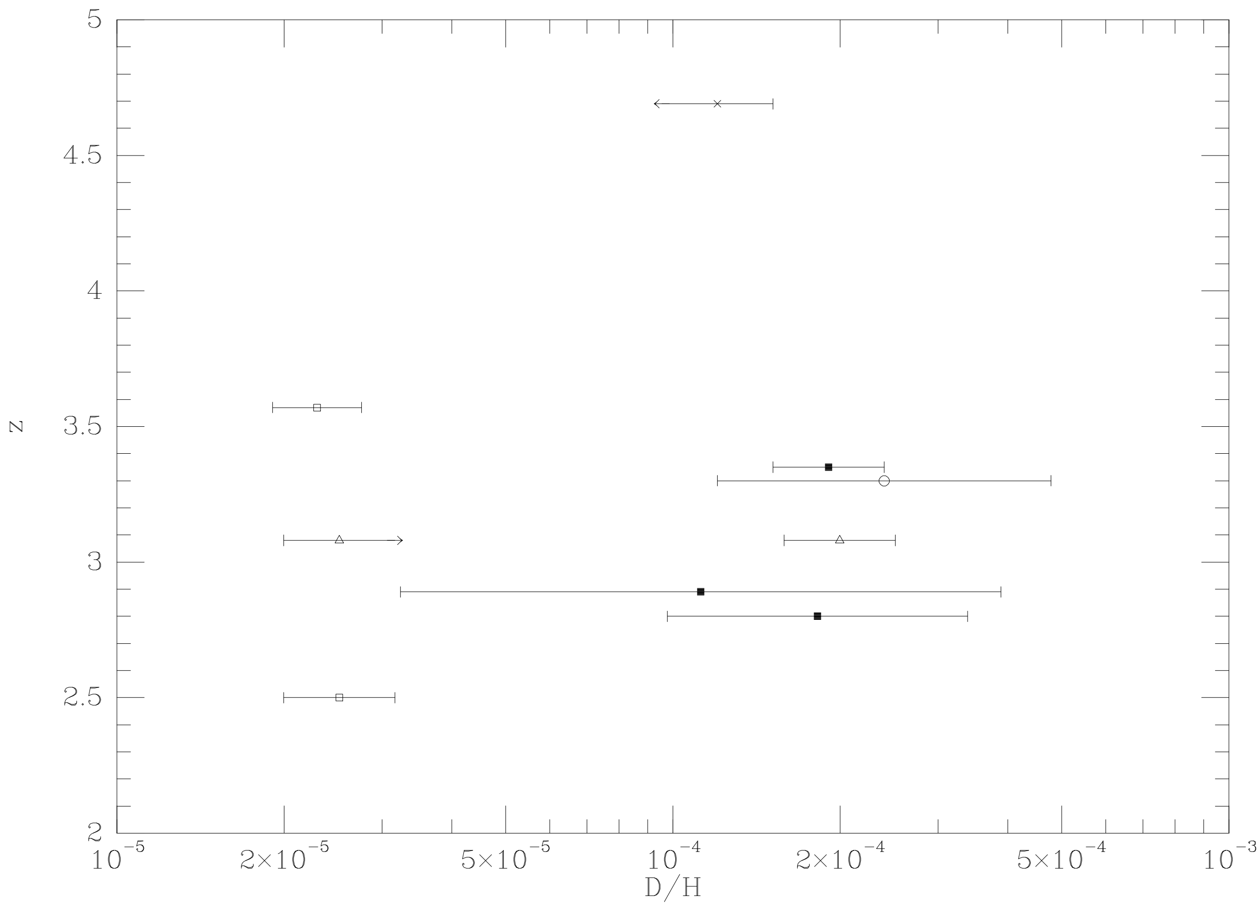

Figure 1: A summary of the D/H measurements in quasar absorption systems. The observations were made by (○) Carswell *et al.* (1994) and Songaila *et al.* (1994), (■) Rugers & Hogan (1996a,b,c), (△) Carswell *et al.* (1996), (×) Wampler *et al.* (1996), and (□) Tytler, Fan, & Burles (1996) and Burles & Tytler (1996). The Rugers & Hogan (1996a) (■) point and the (○) point have been separated in redshift for clarity. See the text for general details.